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**DISTRIBUTED BRAGG REFLECTOR
USING AlGaIn/GaN**

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BACKGROUND OF THE INVENTION

The invention describes a Distributed Bragg Reflector and method for making utilizing multiple layers of AlGa_N/Ga_N and, more particularly, utilizing an interlayer to achieve sufficient reflectivity for a vertical cavity laser.

The growth of epitaxial distributed Bragg reflectors (DBRs) with high crystalline quality is important in the successful development of infrared and red vertical-cavity surface-emitting lasers (VCSELs). The development of III-Nitride-based VCSELs for short-wavelength (visible and ultraviolet) applications requires the preparation of crack-free, highly reflective (that is, high R) (Al,Ga)_N/Ga_N DBRs. Difficulties arise in the preparation of crack-free highly reflective (Al,Ga)_N/Ga_N DBRs owing to the large lattice mismatch between Ga_N and AlN (approximately 2.4%).

Because multiple passes of optical waves are required in VCSELs due to a short cavity (gain) length, highly reflective mirrors (typically $R > 99\%$) are required for low threshold operation. The low contrast in index of refraction between AlN and Ga_N (and thus the ternary alloys) necessitates the use of a large number of pairs of mirrors to achieve such reflectivities. Someya and Arakawa (Someya, T., and Arakawa, Y., Appl. Phys. Lett., 1998, 73, 3653-3655) reported the crack-free growth of a 35-pair Al_{0.34}Ga_{0.66}N/Ga_N DBR with reflectivity up to 96% at 390nm. It was emphasized in that work that the thickness of the (high temperature-grown) Ga_N layer must be restricted to 0.4 μm or less to avoid sample cracking. Langer et al. (Langer, R., Barski, A., Simon, J., Pelekanos, N.T., Konovalov, O., Andre, R., and Dang, L. S., Appl. Phys. Lett., 1999, 74, 3610-3612) reported a maximum reflectivity of 93% at 473nm with 30 pairs of Al_{0.41}Ga_{0.59}N/Ga_N DBRs. Krestnikov et al. (Krestnikov, I., Lundin, W., Sakharov, A., Semenov, V., Usikov, A., Tsatsul'nikov, A., Alferov, Zh., Ledentsov, N., Hoffman, A., and Bimberg, D., Appl. Phys. Lett., 1999, 75, 1192-1194) employed a 1.1 μm Al_{0.08}Ga_{0.92}N

template on sapphire for stress compensation and showed a reflectivity of 96% at 401nm with 37 pairs of $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ DBR mirrors. More recently, Ng et al. (Ng, H., Moustakas, T., and Chu, S., Appl. Phys. Lett., 2000, 76, 2818-2820) explored DBR mirrors consisting of binary AlN and GaN for increased contrast in the index of refraction. A 99% reflectivity at 467nm was obtained with one specific structure that employed approximately 20 to 25 pairs of DBR mirrors. A network of cracks was observed which was attributed to the large tensile stress between the two binary compounds. Kim (U.S. Patent No. 6,306,672, issued on Oct. 23, 2001) describes the formation of DBRs for use in a VCSEL diode where low refractive index air layers are incorporated into the DBR to achieve desired reflectivity. Etching is used to form air layers out of conventional AlGaIn or GaN material. These DBRs are utilized in forming a VCSEL diode. Waldrip et al. (Waldrip, K.E., Han, J., Figiel, J.J., Zhou, H., Makarona, E. and Nurmikko, A.V., Appl. Physics Letters, 2001, 78, 22, 3205-3207; incorporated herein by reference) describe the use of interlayers in DBR structures to address the mismatch of the AlGaIn/GaN layers and achieve high reflectivity DBR structures without cracks.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows (a) a standard AlGaIn/GaN DBR structure grown on a GaN nucleation layer on top of a sapphire substrate and (b) the resulting stress evolution.

FIG. 2 shows (a) a AlGaIn/GaN DBR structure grown on a GaN nucleation layer on top of a sapphire substrate with an interlayer and (b) the resulting stress evolution.

FIG. 3 shows (a) a 60-pair AlGaIn/GaN DBR structure grown on a GaN nucleation layer on top of a sapphire substrate with an interlayer and (b) the resulting stress evolution.

FIG. 4 shows (a) a AlGaIn/GaN DBR structure grown on a GaN nucleation layer on top of a sapphire substrate with three interlayers and (b) the resulting stress evolution.

DESCRIPTION OF SPECIFIC EMBODIMENTS

A Distributed Bragg Reflector is formed, comprising AlN or AlGaIn interlayers that effectively control mismatch-induced stress and suppress the formation of cracks that

otherwise occur during growth of (Al,Ga,B)N/(Al,Ga,B)N epilayers, such as layered AlGa_N directly upon Ga_N. DBRs utilizing AlGa_N/Ga_N layered pairs on a substrate are well known (see FIG. 1a for an example of 30 pairs of Al_{0.20}Ga_{0.80}N/Ga_N on a 1 micron Ga_N nucleation layer) but have had limited effectiveness with lower reflectivity due to the stresses and crack formation induced by the lattice mismatch in the layers (FIG. 1b shows the in situ tensile stress-thickness developed as a function of thickness with an initial growth stress of 1.24 GPa). The average value of the saw-tooth slope changes is 2.49 ± 0.4 GPa, which agrees reasonably well with the expected tensile stress value of 2.33 GPa based on the elastic mismatch between Ga_N and Al_{0.20}Ga_{0.80}N. Step-like reductions in the stress-thickness trace observed at 1.35 μm and at 2.33 μm indicate the relief of tensile stress through crack propagation and admission of dislocations. Inspection of the surface of this DBR under Nomarski microscope confirmed the presence of cracking networks, with an average spacing below 100 μm .

In the present invention, the employment of at least one interlayer at the beginning of a thick (approximately 5 μm or more) DBR growth leads to a substantial modification of the initial stress evolution. Tensile growth stress can be brought under control and nearly eliminated, as confirmed by an in-situ stress sensor, through insertion of one or more AlN, AlGa_N, or AlN-doped interlayers. Reflectivity (R) values of greater than 0.99 are achieved for wafers greater than two inches in diameter.

In one embodiment of the present invention, a supported DBR structure is formed through a metal-organic vapor phase epitaxy (MOVPE) process wherein a substantially Ga_N nucleation layer is grown atop a substrate. The substrate can be any standard substrate material used in semiconductor structures, such as sapphire, silicon, silicon carbide, lithium gallate, lithium aluminate, and lithium nitrate. These substrates tend to inherently put the overlaying (Al,Ga,B)N/(Al,Ga,B)N layered structure into tension. The (Al,Ga,B)N/(Al,Ga,B)N layered structure is commonly a AlGa_N/Ga_N structure but can be more generally any Group III material-based structure such as AlBN, GaBN, AlGa_N, or AlGaBN material paired with an AlN, Ga_N, or BN material. Indium can also be substituted. For the present invention, (Al,Ga,B)N/(Al,Ga,B)N represents any of the potential Group III material combinations that can be used. The Ga_N nucleation layer should be approximately 0.5 microns thick or greater when a sapphire substrate is used.

The nucleation layer for any system needs to be thick enough to promote continuous growth. In a standard DBR (Al,Ga,B)N/(Al,Ga,B)N layered structure, pairs of (Al,Ga,B)N/(Al,Ga,B)N layered layers are then epitaxially deposited on the GaN nucleation layer (see FIG. 1a for one embodiment using AlGaN/GaN layers), resulting in high tensile stresses. In the present invention, an interlayer, comprised of a material selected from AlN, $\text{Al}_x\text{Ga}_{1-x}\text{N}$ (where $0 < x < 1$), AlBN and doped AlN, $\text{Al}_x\text{B}_{1-x}\text{N}$, or $\text{Al}_x\text{Ga}_{1-x}\text{N}$ materials, with a thickness of greater than approximately 20 Angstroms to less than approximately 1000 Angstroms is deposited on the nucleation layer followed by pairs of (Al,Ga,B)N/(Al,Ga,B)N layers, with the relative amounts of the Group III materials present dependent on the desired application. FIG. 2a shows one embodiment using $\text{Al}_y\text{Ga}_{1-y}\text{N}$ /GaN layers, where again $0 < y < 1$. The inclusion of the interlayer in the structure functions to reduce the tensile stress and even, in the initial several thousand Angstroms, results in a compressive stress in the structure. FIG. 2b shows the resulting stress profile for a 30-pair $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}$ /GaN structure with an AlN (less than 500 Angstroms thick) interlayer deposited on the nucleation layer prior to the AlGaN/GaN pairs. Each $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}$ and GaN layer is approximately 400 Angstroms thick; the actual thickness can be varied as determined by the desired application. The DBR structure can yield a reflectivity value of greater than 99%.

The interlayer functions by partially relaxing and providing a new lattice template for subsequent layer growth. The amount of relaxation is dependent upon the temperature of deposition, annealing conditions, growth mode, Group V/III ratio, thickness and composition of the interlayer. The dopants in the interlayer can include small amounts, generally less than 1%, of materials such as calcium, zinc, silicon, magnesium, carbon, bismuth, oxygen, antimony, and indium. These dopants can also be present in the (Al,Ga,B)N/(Al,Ga,B)N layered layers. The layers can be formed with or without the use of surfactant agents during growth.

In another embodiment, multiple interlayers can be employed in the DBR structure to further eliminate tensile stress. For example, FIG. 3a shows a DBR structure comprising 60 pairs of $\text{Al}_y\text{Ga}_{1-y}\text{N}$ /GaN layers with an AlN interlayer between every 20 pairs. A nucleation layer, such as comprised of greater than a 0.5 μm -thick GaN material, is deposited on a substrate, such as the sapphire substrate depicted in

FIG. 3a, and on the nucleation layer is deposited the first interlayer, where the interlayer can be comprised again of a material selected from AlN, $\text{Al}_x\text{Ga}_{1-x}\text{N}$ (where $0 < x < 1$), AlBN and doped AlN, $\text{Al}_x\text{B}_{1-x}\text{N}$, or $\text{Al}_x\text{Ga}_{1-x}\text{N}$ materials, with a thickness of greater than approximately 20 Angstroms to less than approximately 1000 Angstroms. On top of the nucleation layer are deposited pairs of $\text{Al}_y\text{Ga}_{1-y}\text{N}$ /GaN layers. After at least one pair of $\text{Al}_y\text{Ga}_{1-y}\text{N}$ /GaN layers is deposited, another interlayer can be deposited, onto which additional $\text{Al}_y\text{Ga}_{1-y}\text{N}$ /GaN layers can be deposited. The frequency of the interlayers in the stack of $\text{Al}_y\text{Ga}_{1-y}\text{N}$ /GaN pairs depends on the application. The thicknesses of each of the (Al,Ga,B)N/(Al,Ga,B)N layers are also generally greater than approximately 20 Angstroms and less than approximately 1000 Angstroms.

In one embodiment, an AlN interlayer (nominally 150-Å thick) was inserted between the high temperature GaN layer and the DBR structure. FIG. 2b shows the in situ multi-beam optical stress sensor (MOSS) data. The use of an AlN interlayer reduces the in-plane lattice constant and consequently exerts a compressive stress during the initial growth of AlGaIn/GaN DBR structures. The observed compressive stress gradually decreases and passes through a stress-free region at around 0.5 μm ; a constant tensile stress (approximately 0.62 GPa) is developed and sustained throughout the rest of the DBR growth. The exact origin of the observed stress evolution from compression to tension remains unclear; mechanisms such as grain growth and thin film densification have been invoked in other material systems to explain such a spontaneous occurrence of the tensile stress. In this particular case, the employment of an AlN interlayer delays the occurrence of a tensile stress, reduces the steady-state growth tension, and effectively doubles the critical thickness for cracking. The surface morphology was found to be crack-free over the entire 2-inch wafer. The peak reflectivity, however, only reaches about 78% with a bandwidth of around 12 nm.

In applying these results to the design and fabrication of an AlGaIn/GaN multilayer DBR structure suitable for use in vertical microcavities, modeling based on wave propagation across multiple mediums using the transmission matrix method was performed. The results suggest that 50 to 70 pairs of mirrors are required for a reflectivity exceeding 99% with the use of $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}$ /GaN, due to the small difference in refractive index ($\Delta n \sim 0.08$). Another DBR growth was subsequently performed in

which the number of pairs was increased to 60 and the same structure was grown on an 150 Å AlN interlayer (see FIG. 3a). In situ MOSS data during the DBR growth are shown in FIG. 3b. Again, the saw-tooth-like fluctuations in (stress)*(thickness) resulting from the growth of the alternating DBR layers are superimposed upon the “background evolution” from compression to tension. The observed growth tension (0.58 GPa) implies a cracking critical thickness of 2 μm, which is less than half of the total thickness. The surface of this sample, which has a total thickness of 5.7 μm (4.7 μm from the DBR and 1.0 μm from the GaN underlying layer), exhibited a low density of cracks with an average spacing varying from 0.5 mm (near the center) to 50 μm (near the edge) of the 2-inch wafer. In-situ stress measurement indicates that it is the accumulation of the background, “dc” tensile stress energy, not the alternating stress fluctuation between the AlGaIn and GaN layers, which caused the occurrence of cracking. The corresponding reflectivity spectrum showed a peak reflectivity ($\lambda \sim 378$ nm) measured at around 99.1% by a precision reflectometer against a calibrated standard. By varying the individual DBR layer thickness, similar mirrors ($R \geq 0.99$) were obtained with a peak wavelength ranging from 375 to 420 nm. High-resolution x-ray diffraction (Θ - 2Θ) scan along the (0002) diffraction shows the presence of satellite diffraction peaks up to the 13th order.

Although low-temperature GaN and AlN multiple-interlayer schemes have been proposed by Amano et al. (Amano, H., Iwaya, M., Hayashi, N., Kashima, T., Katsuragawa, M., Takeuchi, T., Wetzell, C., and Akasaki, I., MRS Internet J. Nitride Semicond. Res. 4S1, G10.1, 1999) for the purpose of dislocation filtering, Benamara et al. (Benamara, M., Liliental-Weber, Z., Mazur, J., Swider, W., Washburn, J., Iwaya, M., Akasaki, I., and Amano, H., MRS Internet J. Nitride Semicond. Res. 5S1, W5.8, 2000) found that the use of AlN multiple interlayers tended to increase the density of edge-type dislocations through dislocation multiplication. In the present invention, a 60-pair $\text{Al}_{0.20}\text{Ga}_{0.80}\text{N}/\text{GaN}$ DBR structure was grown in which an AlN interlayer was inserted after every growth of 20 pairs (see FIG. 4a, where a total of three AlN interlayers was employed). It is generally expected that at least five pairs of AlGaIn/GaN layers should be deposited before growth of another interlayer. The in-situ stress-thickness vs. thickness of the multiple interlayer DBR is presented FIG. 4b. Once again, the saw-tooth-like features of alternating stress are observed due to the elastic strain between

GaN and AlGaIn layers. Nevertheless, a distinct "drape-like" stress evolution is observed in which the instantaneous growth stress was substantially modified after each introduction of the AlN interlayer. For this particular sample, a compressive stress of 2.3 GPa is introduced after every AlN interlayer. Tensile stress was not observed in any of the 5 μm DBR region, in contrast to the samples with no or only one AlN interlayer. HRXRD was employed to assess the structural quality of the 60-pair DBR with multiple interlayers. When compared with the HRXRD data for a 60-pair $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ with a single AlN interlayer, it appears that the introduction of the three AlN interlayers in a similar structure does not significantly change the microstructural quality. No cracks were observed under Nomarski microscope (50 to 500 times magnification) over the entire two-inch wafer (approximately 5.7 μm -thick film), and the peak of reflectivity remains above 99%, with a bandwidth of 13 nm.

With a DBR so structured, crack-free growth of multiple (60) pairs of $\text{Al}_{0.2}\text{Ga}_{0.2}\text{N}/\text{GaN}$ DBR mirrors has been achieved over the entire two-inch wafer with a maximum reflectivity of at least 99%. By incorporating the in-situ DBRs as bottom mirrors to vertical cavity structures that include AlGaIn/InGaIn multiple quantum well active media and dielectric DBRs as top mirrors, room temperature optically-pumped VCSEL operation at 384 nm has also been demonstrated.

In the formation of the DBR structures of the present invention, metal-organic vapor phase epitaxy was conducted in a vertical rotating-disc reactor. Standard GaN templates were prepared using a two-step nucleation procedure on sapphire. The AlGaIn/GaN quarter-wavelength DBRs and the interlayers were grown at 40 Torr at 1050°C. Ammonia and H_2 flows were set at 2.5 and 5 l/min, respectively. Trimethylgallium (TMG) and trimethylaluminum (TMA) were employed as metal-organic precursors. Growth rates of the AlGaIn and GaN layers were calibrated in-situ using optical reflectometry (from the period of the Fabry-Perot interference fringes) immediately prior to the growth of DBRs.

High-resolution x-ray diffractometry (HRXRD) was performed using a Philips X'Pert System. Real time in-situ stress monitoring based on wafer curvature measurements was performed with a multi-beam optical stress sensor (MOSS) modified for use on our reactor. To determine the wafer curvature, the divergence of multiple

initially parallel laser beams is measured on a CCD camera after reflection of the beams from the film/substrate surface. Changes in wafer curvature induce a proportional change in the beam spacing on the camera. This technique provides a direct measurement of the stress-thickness product during MOVPE of GaN. Slopes of the (stress)*(thickness) traces versus time during deposition cycles can be converted to instantaneous stress once the time scale is converted to thickness scale using growth rates derived from in-situ reflectance measurements.

In another embodiment, interlayers can generally be inserted in any (Al,Ga,B)N/(Al,Ga,B)N layered or doped structure, such as a superlattice structure, to reduce tensile stress and cracking tendency of such a structure. As with the previously described embodiments, the interlayers can be comprised of a material selected from AlN, BN, (Al,Ga,B)N, and such doped materials, with a thickness of greater than approximately 20 Angstroms to less than approximately 1000 Angstroms. Since the function of the interlayer is to relax, thereby providing a new lattice template for subsequent growth, interlayers may be employed to provide a new substrate material for subsequent growth of materials or devices at a new lattice constant to reduce or induce tensile or compressive strain in the system.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.